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STATUS OF WATER RESOURCE SYSTEMS ANALYSIS

by

LEO R. BEARD

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Although great progress has been made in simulating the physical operation of water resource systems, challenging problems still remain. Primarily, these are multi-objective evaluations of physical output and application of operations research techniques. Conflicting and complementary output functions, stochastic input functions, complex physical, legal and social constraints, and system nonlinearities pose ~~great~~ technical difficulties. Development of an optimum plan of water resources (Continued)

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management requires the integration of objectives, such as economic efficiency, environmental protection, ecological management, and social well-being; necessarily, these objectives must be related in terms of a common denominator, or unique objective function. Effective application of operations research techniques, such as linear or dynamic programming, is hindered by the extreme complexity of water resource systems; nonlinearities and interrelationships that change with time and location make optimization particularly difficult. At present, a gradient type of optimization based on detailed system simulation is most useful. Needed is a more realistic and highly sophisticated systems simulation model, capable of accommodating systems of any configuration, inputs, and demand criteria, and containing a framework for operating the system that is sufficiently flexible to respond to all needs. Advances are most promising in the direction of analyzing internal interactions of water resource systems and their impacts on objective functions.

"STATUS OF WATER RESOURCE SYSTEMS ANALYSIS" (1)

By

Leo R. Beard

INTRODUCTION

The Harvard Water Group publication in 1962 of Design of Water Resource Systems furnished an important impetus to the application of systems analysis techniques to water resource studies. Since that time, a great deal of activity in the development of systems application techniques has taken place in universities and other organizations. Because of the extreme complexities of water resource problems, these activities have related to special aspects of the overall problem or to general treatment of the overall problem in a highly simplified manner.

Problems in water resources studies are complicated by many factors. These include conflicting and complementary output functions, stochastic input functions, complex physical, legal and social constraints and system non-linearities. In addition to the great technical difficulties, the diffusion of responsibility for managing a water resource system often makes optimization of the overall output virtually impossible.

Services provided by a water resource development can be grouped into the four general categories of water supply, power generation, low-flow regulation and flood control. Each of these can be divided into subgroups that complement or conflict with each other and each has variations that are both deterministic and stochastic. Services that complement each other at one time might be independent or conflicting at another time. Because of the great variations in requirements from time to time, it is virtually impossible in most cases to summarize these individual requirements in a

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single total that is determinstic or that can be expressed as a relatively simple stochastic variable.

The stochastic nature of runoff quantities (which usually constitute the inputs to any water resource system) is well recognized. Nevertheless, many water resource studies are based on the dangerous assumption that the combination of pertinent historical streamflow sequences will represent an adequate test for the design or operation of a proposed water resource project or system. Such an assumption is usually not satisfactory, and one of the challenging areas of research in water resource systems is the development of models representing stochastic inputs.

The physical constraints and relationships that exist in any water resource system probably introduce more nonlinearities in the analysis than result from any other factor. For example, curves of reservoir outlet capacity and power plant characteristics are often highly nonlinear. Curves of storage versus head or storage versus evaporation are nonlinear. Regardless of whether a linear analysis technique is employed, these factors greatly complicate the analysis.

In some cases, legal and social constraints and requirements can introduce serious complexities into a water resources study. Water rights or other political rights can be highly complex. For example, entitlements for a particular function might exist only for that portion of flows that exceeds a specified quantity on a daily basis and might be constrained at a higher level of flow. It is usually technically difficult to simplify the analysis in such a case, and even if it were technically adequate to do so, the simplification might not be acceptable legally or politically.

As another example, private ownership of a reservoir can constrain its operation to a given service at a specified location, and intermediate or downstream services might be served incidentally but not purposely by that reservoir.

The interaction of nonlinear functions between the various components of a water resource system can add almost immeasurably to the degree of complexity. For example, even in the relatively simple problem of power generation at two tandem reservoirs, it is extremely difficult to evaluate the effect over all future time of generating for a short period in the upstream reservoir as contrasted with the effect of generating the same quantity of energy at the downstream reservoir during the same period. This problem involves the relationship of head differences in relation to storage in the two reservoirs, power plant efficiencies, future potential inflow and releases from the two reservoirs, and many other factors.

PROBLEMS OF SYSTEM SIMULATION

In any systems analysis study, it is necessary to express mathematically the relation between system inputs and the value function for the system outputs. Since the purpose of systems analysis is to modify the system characteristics in such a way as to optimize this value function, the model that relates the value function to system inputs must be highly generalized so that changes in pertinent system components or operation rules are automatically accounted for. At the present time, it appears that the only satisfactory type of model that will accomplish this for water resource systems is a detailed sequential simulation model which relates the stochastic input values to resulting stochastic output values in a generally deterministic

manner. This is the traditional technique used by agencies that have designed and constructed water resource projects.

The deterministic simulation model for a water resource system is simply a model that simulates the day-by-day or hour-by-hour operation of the water resource system with specified inflows at all locations during each interval, specified system characteristics and specified operation rules. Such a model is classified as deterministic, although it certainly will react differently to different stochastic inputs.

The problem of simulating the operation of a water resource system can, in itself, be extremely complex. The task of determining releases at all reservoirs and power generation and diversion quantities at all pertinent locations for a single computation interval is usually treated as the solution of a set of linear equations and constraints. It would be a simple linear programming problem, if it were not for the fact that infeasible solutions frequently occur. These result from service targets that exceed the system capability, and require that a decision on shortages be made. If relatively simple decision criteria are acceptable, it is possible to construct a mathematical model for computer operation that will solve the problem iteratively, but programming the solution can be extremely challenging. To date, some rather elaborate models for simulating the operation of a water resource system have been constructed, but a great deal remains to be done before a really satisfactory model for any complex water resource system becomes available.

In addition to modeling the operation of a water resource system, it is necessary to model the stochastic inputs and stochastic demands of the

system. Computation feasibility usually requires that the basic simulation models for most planning studies be based on a rather long time interval, usually 1 month. Considerable progress has been made in generating monthly values of streamflow, rainfall, evaporation, and water demands. However, the best available models still leave much to be desired, and the problem of generating stochastic quantities for shorter intervals (needed in some planning studies and many operation studies) has only been touched upon. Some models for single variables exist, but multivariate short-interval models pose more difficult problems.

Basically, the generation of hydrologic quantities involves the determination from recorded events of all pertinent stochastic and correlation characteristics of the quantities involved. Even with relatively simple multivariate models, such as linear regression, the problems involved can be quite challenging. In particular, techniques for deriving a set of correlation matrices and statistical distributions that are mutually consistent throughout space and time from incomplete data matrices have never (to the writer's knowledge) been demonstrated in mathematical literature. Many approximations are necessary, and these reflect seriously on the validity of results.

At present, it is possible in most cases to generate monthly hydrologic quantities and to construct monthly system simulation models that are reasonably satisfactory for most study purposes. However, there are many cases where the stochastic models in particular are inadequate, and much development remains to be done. The problem of generating interrelated short-period hydrologic quantities for use in flood control or pumped-storage studies is far more difficult and has virtually not been attempted.

DEFINITION OF RESPONSE FUNCTION

There are many objectives for water resources development. Traditionally, the economic objective of maximizing national income has been generally employed, but now other objectives involving social, political, ecological and environmental values have become highly important. Even considering only the economic evaluation of system outputs, the problem is highly complex.

In general, water resource services are provided on a contract or guaranteed basis. Services in excess of these firm commitments are usually of very minor value, because the community is unprepared to utilize them effectively. On the other hand, shortages in such services can be extremely costly, because society has integrated these supplies into its delicate structure, and shortages can disrupt social activity seriously. Accordingly, objective functions can be highly nonlinear.

Flood control damages or benefits are unique in that they are usually associated with simple parameters of river flow or stage. Flood damages can be measured by actual field surveys, and most of them can be readily expressed in monetary units. The benefits for other functions are usually evaluated as alternative costs, rather than real benefits, and criteria for evaluating surpluses or shortages in these quantities virtually do not exist.

As difficult as a realistic evaluation of economic effects is, the evaluation of social, environmental and other effects is far more difficult. Furthermore, it appears that a common denominator for comparing these various types of effects will be very difficult to formulate. The value of clean air or clean rivers or of human life or of beauty in terms of dollars or any other common denominator will be difficult to determine.

There is currently some thought that a project planner can develop various plans that are responsive to various objectives and that a legislative body can select from these the plan that is most desired by the community. If there is not a common denominator for values of all objectives, then the various plans developed could be optimized in relation to only one set of objectives at a time. It is very unlikely that the overall optimum plan would be contained in any number of plans developed in this manner. Consequently this general approach would not result in an optimum plan and very likely would not be close to optimum.

Perhaps the most important need at present in relation to defining value functions is a need to develop a common denominator by which values for all objectives can be compared and coordinated.

An additional problem of evaluating outputs (which has not been given attention generally) is the problem of forecasting values that society will place on outputs in the future. Many existing projects that were fully responsive to values held when the projects were built are now condemned--not because they did not respond to contemporary needs and values, but because they do not now properly serve the new needs and new values.

ANALYTICAL SOLUTION TECHNIQUES

Techniques available for deriving optimum plans of development in water resources studies include dynamic programming, linear programming, and a variety of search techniques. Often a combination of these techniques is used in a multilevel optimization structure, using the general (multi-stage) principle of dynamic programming. This principle consists of isolating a portion of the problem and solving that portion for all possible states

of the pertinent variables. A traditional example of this is the construction of a cost curve for a reservoir, where the single state variable, size of reservoir is related to cost by developing the least costly type of dam, spillway, etc., for each size of reservoir. This cost curve can then be applied in the overall problem without further recourse to design details until the design is implemented.

As the number of state variables in any dynamic programming problem increases, the number of combinations of values for all state variables increases rapidly, and the problem soon become computationally intractable. However, the dynamic programming technique is powerful in those applications where it is computationally feasible, and some progress is being made in reducing the amount of computation required for larger numbers of state variables. Unfortunately, the solution of a water resource system problem involves a large number of state variables, and consequently dynamic programming techniques are usually employed in only a portion of the overall problem where state variables can be reasonably isolated in groups of 4 or less.

Linear programming is also a powerful computation technique. The optimum solution to a problem defined by thousands of linear constraints and a linear value function can be solved readily. The principal difficulty in the application of this technique lies in the approximations of many nonlinear functions. In cases where the constraints overlap to the extent that no feasible solution exists, which condition is quite common in water resource problems, it is necessary to relax constraints in an orderly manner, and this adds greatly to the programming and computation problems.

In view of the complex nature of functions relating water resource system inputs to value functions, it appears that the most practical overall optimization technique is a search technique. This would consist of evaluating the project operation of the system using a determinstic simulation model and stochastic inputs, changing system parameters in a logical manner, and repeating this process until significant improvement is no longer obtained. Some sophisticated search techniques have been developed, such as "steepest ascent". There is a large amount of computation involved in this process, particularly if stochastic inputs must be accurately representative of future potential. Improvement of this technique in the near future will probably involve studies of the internal structure of the system that will point to a logical assessment of the effects of parameter changes. Changing a parameter arbitrarily and computing the objective function is an expensive process.

ANTICIPATED DEVELOPMENTS

There appears to be a critical need for the planning and design community to convey to the academic community in detail the real problems that must be met in the planning, design and operation of a water resource system. Until real problems are documented in sufficient detail to provide a realistic test of systems analysis approaches, there is inadequate opportunity for the academic community to carry studies to the practical application stage.

It appears that the first practical development will consist of a realistic and highly sophisticated systems simulation model. This model must be capable of accommodating systems of any configuration, any inputs

and any demand criteria. It must also contain a framework for operating the system that is sufficiently flexible to respond to all needs. Considerable progress has been made in this area. Future progress will be slow, because the most complex aspects of the problem remain to be solved. Possibly more than one basic model will be required, and many speciali ed models designed for higher computation efficiency may be appropriate.

The next development that will be needed is the definition of evaluation procedures and criteria that realistically represent values that society places on the system outputs. A unique objective function is essential if an optimum plan of development is to be obtained. This means that all of the water resource objectives must be evaluated accurately and must be related in terms of a common denominator. The scope of water resource objectives has been expanded drastically in the past 15 years, but the problems of evaluating system outputs in terms of these objectives and of developing a common denominator are only now being attacked.

Perhaps new operations research techniques will be developed that supplement the basic concepts of linear programming, dynamic programming, simple gradient techniques and other techniques now being used. In any event, these techniques must be developed far beyond their present capability. At the same time, computer hardware and software capabilities will increase, and the combination of these various developments might make possible a reasonable solution of the complex water resource systems problems.

Probably the most promising development, particularly during the next decade, will consist of problem-oriented analytical techniques. These will consist of assessing critical features of a water resource system model and using these to deduce the effects of parameter changes on system outputs and on the value function. An example of this is the critical-period analysis for determining yield, where data on the length of time

from full to empty reservoir (or to minimum storage) and the shortage or surplus of water can be used to compute yield accurately in a linear system (or to successively approximate it in a nonlinear system). More sophisticated techniques might involve such things as computing the total energy in storage at any one time (as it will be supplemented by anticipated inflows) in order to program power generation. Optimization of system operation might best be accomplished through use of a sequential simulation, maintaining a systematic record of sequential system states in relation to pertinent constraints, operating rules, inputs and outputs.

In general, the writer feels that a break-through in applying systems analysis techniques to water resource problems will result only from long and intensive efforts by scientists who thoroughly understand the intricate features and complex nature of many water resource systems. This will require a better understanding by the practicing engineer of the principles and limitations of systems engineering.

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